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Model Predictive Individual Pitch Control Based on Local Inflow Measurements

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ABSTRACT

As wind turbines become larger, the area swept by the rotor will contain larger variations in wind speed and direction causing varying loads on the turbine. Some of these loads can be alleviated using individual pitch control. In this study, a previous study on individual pitch control is extended to include model predictive control based on preview measurements of the local inflow. The model predictive controller is tested through simulations and the performance of the controller is compared to the performance of a collective pitch controller and a linear quadratic individual pitch controller. The performance of the model predictive controller is tested in both turbulent and deterministic inflow. The results show that in all simulated cases the two individual pitch controllers outperforms the collective pitch controller, but the model predictive controller does not appear to perform significantly better than the linear quadratic.

Keywords: Inflow measurements, load alleviation, Model predictive control, individual pitch

1 INTRODUCTION

The dominating sources of varying loads on wind turbines are the deterministic and stochastic variations in the wind. As the rotor sizes increase, the swept area of the rotor will contain a growing variation in the wind speed and direction due to wind shear, veer, turbulence etc., and due to other effects such as wakes from nearby turbines. These variations in the wind will cause variations in the loads induced on the turbine, which cannot be alleviated using collective pitch control. Hence, more advanced control techniques are required.

Numerous attempts have been made to develop advanced control schemes for alleviating the varying loads. The suggested methods can be categorized in two categories; lifting surface methods such as flaps, and pitch control methods, the latter being the topic of this paper. Early attempts on implementation of pitch control for load alleviation were based on knowledge from the helicopter technology and is referred to as cyclic pitch control [3, 4]. Cyclic pitch is based on using multi-blade transformations on the blade root bending moment signals to gain non-rotating tilt and yaw moments which were used in classical PI control schemes. Control actions were transformed back to the rotating frame of reference using the reverse multi-blade transformation.

Recent work on individual pitch control (IPC) includes further developments of the methods suggested in [3, 4], cf. [2], gust load reduction using nonlinear estimators to estimate inflow parameters based on blade root bending moments [7], and methods based on combining LIDAR wind speed measurements with turbine models[8, 5]. A more thorough review on methods for load alleviation using both individual pitch and lifting surface methods can be found in [1]

The above mentioned methods, except the ones based on LIDAR, are based on structural measurements such as blade root moment and tower bottom moment. Since the structural measurements are effects of varying wind conditions acting on the turbine, using these for control will lead to an inherent time lack. In [10], a control method based on local inflow measurements is suggested. This approach have the advantages of being based on the actual input/disturbance to the turbine. The present work is based on the method suggested in [10]. The objective of this study is to explore the possibility of improving the inflow measurement based method by including preview measurements in the control system. To take advantage of the preview measurements a model predictive controller (MPC) is implemented. The performance of the MPC is compared to the performance of a traditional collective pitch controller and a linear quadratic individual pitch controller without preview (LQR).

2 CONTROL CONCEPT

For full details cf. [10]. The control scheme is based on measurements of angle of attack and relative velocity at some radial position on the blades. These measurements could come from blade mounted pitot-tubes or from other types of transducers such as LIDAR. In this study, it is assumed that perfect measurements of angle of attack and relative velocity are readily available, no modeling of the actual transducer is performed. The basic idea of the control scheme is to split actions based on angle of attack variations from actions based on variations in relative velocity. Control actions due to either type of variation is added to the collective pitch signal and do not affect the average pitch.

The actions based on the angle of attack variations are based on the idea of keeping the angle of attack the same for all blades. The difference between the angle of attack of one blade compared to the average angle of attack of all blades is used as reference signal for the pitch controller. Hence, the control action based on the angle of attack variations does not affect the collective pitch regulation, which is only concerned with average value. The reference pitch signal based on the angle of attack variations is defined as:

$$\theta_{\delta i,a} = \bar{\alpha} - \alpha_i \tag{1}$$

where $\theta_{\delta i,a}$ is the desired pitch angle increment of blade i, α_i is the angle of attack at a radial position on blade i, and $\bar{\alpha}$ is the average angle of attack of all blades.

The variations in relative velocity cannot be directly translated into reference pitch angles, and are therefore feed to the pitch controller using gains extracted from a cyclic pitch design [10]. The reference pitch signal due to the relative wind speeds is calculated as:

$$\theta_{\delta i,b} = (V_{i,x} - \bar{V}_x)K(\omega, \theta_{col}) \tag{2}$$

where $\theta_{\delta i,b}$ is the desired pitch angle increment for blade i, $V_{i,x}$ is the in-plane wind speed of blade i, $\bar{V}_x$ is the average in-plane wind speed of all blades, and $K(\omega, \theta_{col})$ is the pitch gain, which is a function of both rotational speed, ω, and collective pitch angle, θ_{col}. The gain $K(\omega, \theta_{col})$ is obtained from simulations with a cyclic pitch controller. The in-plane wind speeds are calculated as:

$$V_{i,x} = V_{i,rel} \sin(\alpha_i + \theta_i) \tag{3}$$

where θ_i is the current pitch angle of blade i. The total reference pitch increment for each blade is then given as:

$$\theta_{\delta i} = \theta_{\delta i,a} + \theta_{\delta i,b} - \left[\tan^{-1}\left(\frac{\bar{V}_y}{V_{i,x}}\right) - \Theta\right] \tag{4}$$

where $\bar{V}_{i,y}$ is the average wind speed in the out of plane direction, and Θ is defined as:

$$\Theta = \frac{1}{B}\sum_{i=1}^{B} \tan^{-1}\left(\frac{V_{i,y}}{V_{i,x}}\right) \tag{5}$$

where B is number of blades. The last term of Equation (4) is subtracted to subtract the angle of attack variations caused by the actions based on the relative velocity variations.

The pitch reference increment $\theta_{\delta i}$ is added to the collective pitch reference, θ_{col}, and passed to the pitch controller. Hence, the reference pitch for blade i is defined as:

$$\theta_{i,ref} = \theta_{col} + \theta_{\delta i} \tag{6}$$

where θ_{col} is the reference pitch given by the collective pitch controller.

3 Models and Simulation Software

In the present study, simulations are performed using the aeroelastic code developed at Risø-DTU, HAWC2 [9]. The turbulence is simulated using Cartesian boxes with Mann turbulence [11]. The wind turbine model used for the simulations in this study is of a turbine with a hub height of 59 meters, a rated power of 2 MW, and a rated rotor speed of 1.8 rad/s. The pitch servo is modeled as a 2nd order filter given in continuous state space form as:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} \end{aligned} \tag{7}$$

where

$$\mathbf{x} = \begin{bmatrix} \dot{\theta}_i \\ \theta_i \end{bmatrix}, \qquad \mathbf{A} = \begin{bmatrix} -2\xi\omega & -\omega^2 \\ 1 & 0 \end{bmatrix}, \tag{8}$$

$$\mathbf{B} = \begin{bmatrix} \omega^2 \\ 0 \end{bmatrix}, \qquad \mathbf{C} = [\mathbf{0} \quad \mathbf{1}] \tag{9}$$

where the eigenfrequency and damping is set to $\omega = 1$ and $\xi = 0.7$, respectively.

4 Control design

In this paper, two different control strategies for tracking the reference pitch are tested; a standard optimal linear quadratic regulator, and a model predictive controller which uses measurement from leading blades as preview measurements.

To enable reference tracking using the LQR, the controller is designed using the pitch servo model given Equation (7) augmented with an integrator. The control gains are calculated using standard linear control theory, c.f. [6].

The preview reference pitch angles for the MPC are available from inflow measurements from the blade leading in the rotation. Hence, if blade 2 follows blade 1 when the rotor spins, the prediction horizon of blade 2, $\theta_{2,ref}$, is found by applying Equation (4) to the angle of attack and relative velocity measured by blade 1 (α_1 and $V_{1,rel}$), see Figure 1. The applied MPC is design in accordance with the description in [12].

5 Preliminary Results

The controller is tested through simulations in both deterministic and turbulent inflows (turbulence intensity: 10%). In both cases a power law vertical wind shear with a power coefficient of 0.5 is imposed on the inflow. In Figure 2 and 3 sections of the resulting time series for the deterministic and

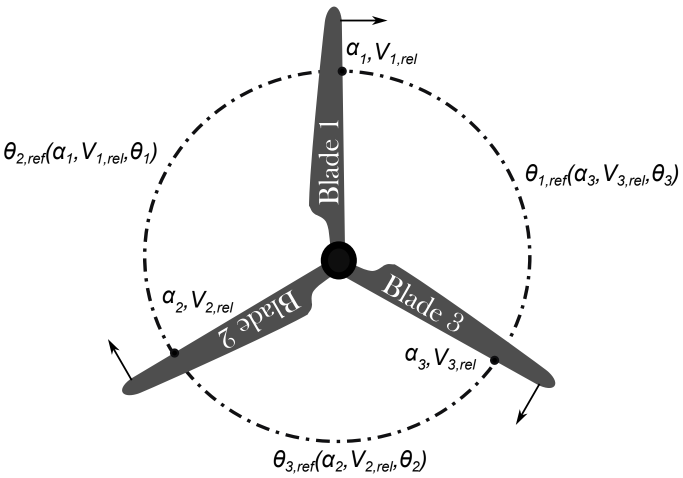

Figure 1: Illustration of the sampling of the prediction horizons

turbulent case is shown. The Figures show angle of attack, pitch and blade root bending moment for situations with both the collective, and the two different individual pitch controllers.

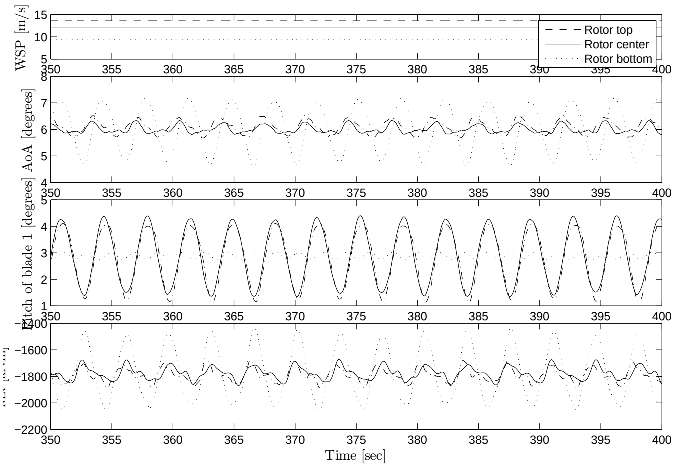

Figure 2: Results of simulations with the three different controllers in deterministic inflow with a power law vertical wind shear with at power coefficient of 0.5. From the top: wind speed, angle of attack, pitch, and blade root bending moment $\cdots$: Collective pitch, $-\cdot-$: LQR, —: MPC.

From Figure 2 it is seen that for the case with a deterministic inflow to the turbine the variations in angle of attack are greatly reduced when using IPC and that the amplitudes of the variations are smallest when applying the MPC. The pitch signal for the IPC controllers are similar, but as expected the signal of the LQR has a slight phase shift compared to the signal of the MPC. Inspecting the blade root bending moment, it is observed that there is very little difference in the signals from the LQR and the MPC, but they both have significantly smaller amplitudes than with the collective pitch controller. Hence, for the deterministic case no benefit are found for the MPC compared to the original

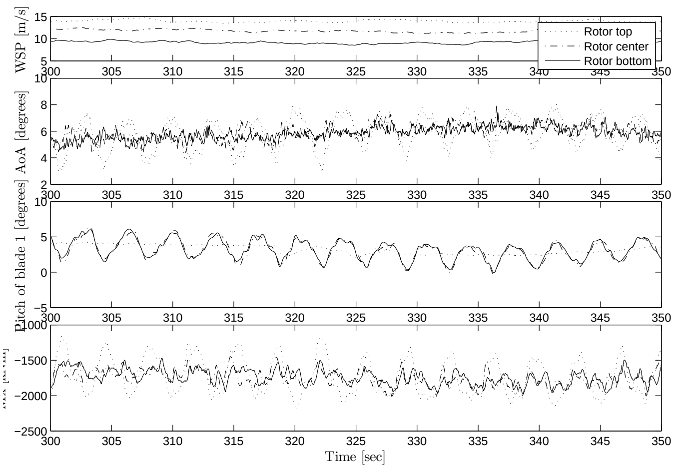

Figure 3: Results of simulations with the three different controllers in turbulent inflow (turbulence intensity: 10%) with a power law vertical wind shear with at power coefficient of 0.5. From the top: wind speed, angle of attack, pitch, and blade root bending moment $\cdots$: Collective pitch, $-\cdot-$: LQR, —: MPC.

LQR.

Inspecting the turbulent case shown in Figure 3 it is seen that the variations in angle of attack now seem to be similar for both the IPC's, however still much smaller than with the collective pitch controller. As expected, the pitch signals for the turbulence cases are more irregular than for the deterministic case, but a slight phase difference between the LQR and the MPC is still visible for the low frequency contents. Finally, inspecting the blade root bending moments for the turbulent case, it is seen that again the amplitudes of both IPC's are much smaller than for the collective pitch controller. Generally, the amplitudes resulting from either IPC are similar. However, some spikes in the LQR blade root bending moment signal are not present in the signal from the case with the MPC, e.g. at $t = 319$, $t = 329$, $t = 332$ and $t = 336$. Anyhow, these reductions might be coincidences, and a larger study is needed to conclude anything in general.

6 DISCUSSION

From the results presented above, it seems that there are only limited benefits from using preview measurements for the local inflow measurement based controller. However, so far only simple cases with and without turbulence have been tested. The preview measurements might provide more benefits in the presences of e.g. gusts or wakes from nearby turbines. In such cases the preview measurements might help alleviate the peak loads. Furthermore, additional benefits of preview measurements might emerge if actual preview measurements were used. In this study, it is assumed that the flow is stationary in the 120 degrees separating the blade at which the flow is measured and the blade being controlled by the model predictive controller. This assumption is not entirely valid, and if it is violated the IPC might increase loads instead of alleviating them. Other upwind pointing measurement system such as LIDARs could be applied to gain more accurate preview measurements.

7 Conclusions and Future Work

In this preliminary study a model predictive controller for individual pitch control based on the ideas in a previous study was implemented and tested in cases with both deterministic and turbulent inflow. The performance of the controller was compared to the performance of a linear quadratic controller and a baseline collective pitch controller. In the deterministic case it was seen that both of the individual pitch controllers greatly reduced the variations in blade root bending moment. However, no additional benefits were observed for the model predictive controller compared the linear quadratic. In the turbulent case it appears that the model predictive controller might be able to alleviate some of the peaks in the blade root bending moment present in the results from the linear quadratic controller. However, more elaborate studies are needed to investigate this. Further work will include more elaborate simulation studies to better map the performance of the new controller and simulations with wakes and extreme gust. Furthermore, preview measurements from simulated LIDARs will implemented.

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